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A CONTRIBUTION TO THE STRUCTURE AND DESIGN OF THIN-WALLED CONSTRUCTION PARTS OF GLASS-FIBER REINFORCED PLASTIC LAMINATES* SUBJECTED TO AXIAL AND TANGENTIAL STRESSES

by

H. Landmann

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ABSTRACT: Glass-fiber plastics (GFP) are examined as a construction material for load-bearing parts which the author calls "shells." GFP's are found to compete with other structural materials very satisfactorily. GFP is defined as a combination of glass fibers and plastics in which the plastics predominate, whereas the intrinsic carrier material is glass fiber. Various combinations of the two basic components are described and investigations with different aircraft structural elements are discussed. Most of the investigations deal with an equally divided force flow in relatively thin-walled laminates of glass fibers and plastics of various types and from different manufacturers. The influence of structure on strength and rigidity is studied and the tensile strength of laminates of various glass fabrics as a function of load direction is calculated. An example of a force-originating point is illustrated in reference to the connection of a frame structure of steel tubes to a truncated cone-shaped GFP shell. The author makes several proposals for the stress analysis of laminates. This article is the text of a lecture given at the Department of Aeronautical Engineering at the Polytechnical Institute in Budapest.

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H. Landmann

1. Introduction

If a designer wants to develop a structural element for a specific purpose he must know the specification or have experience with the materials to be used as well as any special characteristics that they might have, in addition to knowing the external forces that will be involved and the general dimensions of the structural part in question. This then puts him in a position to be able to design the cross-section that is under stress in such a manner that a sensible relationship is attained between strength or rigidity, on the one hand, and increase in mass, on the other. This is the purpose of his engineering handbook which gives most of the right answers provided standard materials are being used. The failure of a machine part that is made from it is almost always never a material problem, but rather an incorrect load assumption, local stress peaks caused by improper cross-section transitions, exceeding the prescribed total

*Text of a lecture given at the Department of Aeronautical Engineering at the Polytechnical Institute Budapest held in July 1963.

number of load alterations, various corrosive influences and similar factors. It might be possible in this connection that the safety factors are too low with regard to fracture, yield value, etc. It should be refrained, however, if we know, for example, in designing aircraft that safety factors with regard to fracture that are down to 1.5 or 1.1 with regard to yield stress or $\sigma_{0.2}$ boundary have proven to be quite reliable. It is assumed, however, that

1. that the theory that is used in calculating the strength is suitable in reality as, for example, in stress overlap, stress distribution in the bending cross-section or in the force pattern of the local force introduction,

2. the assumed loads are carefully calculated and varified through practice,

3. the strength coefficients of the material represent the guaranteed minimum values.

Up to now the last assumption has been the main reason for the unfortunate fact that designers using GFP (glass-fiber reinforced plastics) have still been met with great difficulties. Guaranteed minimum strength, somewhat along the idea of the relatively small variations within several charges of the same metal alloy and of the same condition of the material at the time of supply, is practically non-existant for GFP. The fact of the matter being then that this "minimum value" is so sharply reduced that a designer is not longer so interested in such a "minimum valued" material because the final product would be so difficult and consequently to expensive.

In so doing, we raise an important point in that we want to answer the question - at least in connection with large structural parts - right in the beginning as to whether GFP is really the most suitable material for the job. In some cases we will have to say yes

without any further ado, e.g., when certain specific characteristics are absolutely necessary as: greatest possible bendability (in fishing rods), ability to absorb a great deal of mechanical energy (protective helmets), smallest possible thickness (in equipment, gages, templates for large structural parts), good light transmission (in certain elements in construction engineering), good electric insulation and heat dampening. In other cases, especially where there is no problem with regard to weight reduction, the use of GFP could be very uneconomical.

Within the scope of this article, GFP interests us primarily as a construction material for load-bearing parts which we will refer to as "shells", i.e., surface elements (flat, one or several indentations) which are suitable for conducting axial and tangential forces along their plane, where, as a rule, the requirement is for minimal increase in weight (light construction!). The use of GFP can be very suitable, yes, even recommended for these assignments, especially in those places where other desired properties such as good appearance, insensitivity to atmospheric and chemical agents, ease of manufacture (e.g., handmade in connection with complicated forms), long service life, as well as other qualities already mentioned above can be attained at the same time.

Light construction of an already known material of high strength, high E or G modulus at the same time having a small thickness!

As comparative magnitudes we developed concepts such as

$$\text{"breaking length"} = \frac{\sigma_{zB}}{\gamma} = \frac{\sigma_{zB}}{\varrho \cdot g} \,[\mathrm{km}] \qquad (A)$$

$$\text{"elasticity length"} = \frac{E}{\gamma} = \frac{E}{\varrho \cdot g} \,[\mathrm{km}]$$

in which the high-quality GFP satisfactorily compete with known structural materials (Figure 1).

This arbitrary comparison of a certain GFP design with a different high-quality construction material shows that the "breaking length" σ_{ZB}/γ in the same order of magnitude as wood and Dural is, however, about double as much as St. 60. On the other hand, the "elasticity length" E/γ in the selected GFP quality is barely 40% that of steel and Dural or 56% of aircraft woods. This indicates that it is easier to construct light with GFP rather than heavy.

The Mechanical Values for Various Structural Materials

Material	Stress-Strain Resistance $\sigma_{ZB} \cdot 10^{-2}$ kp/cm^2	E-Modulus $E \cdot 10^{-6}$ kp/cm^2	Spec. Wht. γ kp/dm^3	Breaking Length $\frac{\sigma_{ZB}}{\gamma}$ km	E-Length $\frac{E}{\gamma}$ km
St. 60.11	60	2,100	7.8	7.7	2690
Dural Al Mg Cu	43	0,725	2.8	15.4	2590
A/C Wood 4002	8	0,100	0.56	14.3	1790
GFP of Cross-Webbed Glass in the amount of 57%	28	0,180	1.8	15.6	1000

Fig. 1.

We, however, anticipate the development of our concepts! Unfortunately, in practice it is not possible to simply take the characteristic values for GFP from tables. If we find data as those indicated in the above table then they must have been obtained at least from a laboratory and, as a rule, not reproducible. This, too cannot be expected because all GFP's are different and cannot be concretely defined and especially not as a homogenous material. The name itself already suggests that we are dealing with a combination of glass fibers and plastics in which the accent is still in the plastics, whereas the intrinsic carrier material is the glass fiber.

From this point of view the designation GFP is not a happy one. But it is the best we can do.

The above mentioned combination of two basic components clearly conceals the infinite variety of variation possibilities. Subgroups present some of the following problems, to mention a few:

1. influence of the glass portion $\frac{\text{amount of glass}}{\text{total mass}}$,

2. influence of the type of glass (alkali-content)

3. influence of the type of resin,

4. influence of the element fiber strength,

5. influence of the size or desize,

6. influence of the subsequent treatment of the textile (type of webbing, matting type),

7. influence of the finish,

8. influence of the activiators used,

9. influence of the age hardening process (cold - hot),

10. influence of the experience, care and cleanliness in manufacturing the test specimen,

11. influence of the various types of stress and test specimen shapes,

12. influence of the angle between the force direction and the direction of the main fibers,

13. influence of time (creep, stress fatigue), and

14. influence of future operating temperature (temperature and humidity).

There should be no other construction material which has as many similar influences on the parameters of the mechanical characteristics as is the case with GFP and this is the reason why clear and precise data could not be obtained up to now. One consolation in this very

dark area is that we at least recognize the tendency in this partial problem. Adverse influences can be eliminated from the beginning or we can limit ourselves to partial influences that lead to satisfactory results.

It is hoped that at least in satisfying certain unavoidable requirements the manufacturing and processing plants, standard values will be available in the foreseeable future according to which GFP construction elements can be calculated, tested and approved. At present, specific investigations under actual operating conditions are still essential if we are to find the optimal solutions for large light-construction parts. In the development of such parts, we should proceed in such a manner, after finishing several pilot models (V_1, etc.) a zero series of the subject device should be built in cooperation with the chemist, engineer, designers, the tradesman, and representative of the shop, who conduct intensive tests and make improvements through use. This procedure should be continued as long as it appears as though improvements can be made. Developments that are made along these lines are time and money consuming and, of course, the more so the less the special experience the plant has with GFP. Plants that want to start with the manufacture of GFP parts can expect that they will pay a great deal to learn. The difficulties that are discussed here regarding the slight amount of data concerning the strength of GFP is, however, only a portion of what is expected.

About 9 years ago when the first preliminary tests were started at my former Institute for Aircraft Construction to build load bearing parts for aircraft from GFP, at first small parts such as control surfaces, and later, however, also large parts such as wings, fuselage and even containers and landing gear struts, we experienced

difficulties of all sorts. We had to painstakingly work out the strength and stiffness values by long test series. We learned what it meant to properly construct materials. From the source of our best wood and metal people we sought to find the most suitable forces and to incorporate them completely in the new material, we determined the source of supply for the new construction material (resin, hardener, accelerator, glass webbing, rovings, etc.) and developed technical possibilities from case to case, and many others.

A great part of our work, of course, also included boardering areas such as paper honeycombs, foams, adhesive resins and technical materials, especially since the GFP sandwich construction appeared to be the most advantageous for our purposes at the time. The monocoque type of construction presents the designer, as is well known, not only with pure strength problems but also with problems dealing with stability when the shells are subjected to pressure, thrust, torsion, or transitional stresses which, as is well known, cannot be handled with thin plates. These buckling, denting and crinkling problems are not to be treated today because the subject was taken up at the January symposium on sandwich elements that was held this year. The present event is to deal with GFP materials, i.e., as pertains to thin-walled laminates, and we have only to talk about problems on strength and elasticity. By far the greatest part of investigations at the time dealt with equally divided flow of force in relatively thin-walled laminates of glass fibers and plastics of various types and from various manufacturers. Laminates of glass-fiber webbing are of no importance for our purposes and were, therefore, not investigated.

The empirical values are the following results of work completed at the Institute:

1. 53 and E-themes in the subject field
2. 8 large proofs
3. 16 theses

by former students

4. 1 dissertation (on Western sandwich problems).

If a great deal of specifically flight-technical material is contained that perhaps is less interesting then, on the other hand, it appears to me that anything so noteworthy would interest a wide circle of people and especially those that are not only interested in plastics that are poorly processed but also those that recognize the possibilities in our GFP light-constructions.

2. Influence of the Structure on the Strength and Rigidity

Undoubtedly the most interesting point in this type of shell is the fact that the designer can or even must design structural parts from case to case using materials that are suitable for his purpose which, of course, are designated under the collective name of GFP and which are, however, surprisingly variable. This brings us to the question of the structure which, in addition to the initial materials used and their space and weight factors, is of decisive importance for the mechanical properties of the glass-resin combination.

It is evident that the strength - at least up to a certain degree-increases with the portion of the fibers that are in the direction of the load. Consequently, the lowest values are expected from laminates of webbings with a small amount of glass and the highest in the case of rods (rovings) with a high portion of glass. Experience, however, shows that the theoretical possible amount of glass of from 88 to 95% (according to the arrangement of the elementary fibers) is neither realizable nor practical. GFP profiles made up of drawn rovings are, for the most part, not more than 70% glass which can easily be

determined from the density of the combination because of the varying density of the glass and the resin. The thin laminates that we are interested in are chiefly produced from glass fibers, i.e., from patterns in which the chain and weft primarily run at a right angle to each other. In patterns of this type in which both t ;e of fibers are equivalent (e.g., in linen, twill, and satinbindings) (1) about the same amount of strength is obtained in both directions whereas the strength in all other directions is less (Figure 2).

Fabrics in which a direction is preferred then, instead of a bi-axial symmetry we obtain only a single axial diagram (2), whereas laminates of irregular glass fiber mattings diagrams are obtained in a circular form (3).

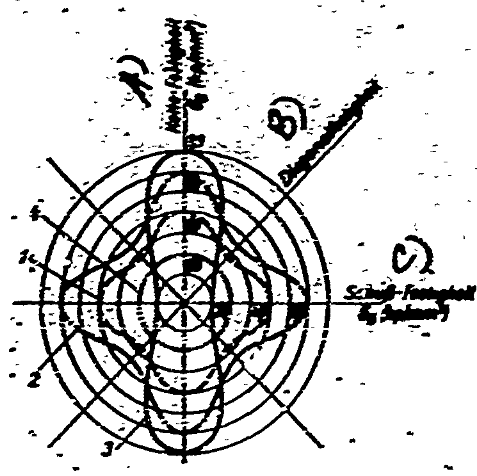

Fig. 2. Tensile Strength of Laminates of Various Glass Fabrics as a Function of the Load Direction. 1. Normal Fabric; 2. H. M. cloth; 3. Chain strengthened Fabric; 4. Matting.

KEY: A) Chain strength; B) Diagonal strength; C) Weft strength.

It is characteristic that quite large strength values are always obtained in the diagonal direction. In cases in which the stress is not present in the diagonal direction (e.g., in tangential or torsional stress) it is applied so that the position of the fabric is canted

45°. If, on the other hand, we are dealing with component stesses - e.g., pushing and pulling or bending and torsion - then the structure of the entire laminate is developed in such a manner that, for example, the normal force components are absorbed by the chain reinforced fabric, but the tangential forces are absorbed by the diagonal fabric which can be arranged quite easily by hand in any series over one another so that the total stress is absorbed optimally.

A possibility of this type in which the material is to be laid out according to "measure" for the actual task designated at the time, is seldom and, therefore, the designer should accept GFP with pleasure. Another example as to how the designer can and will work with the new material, is presented by the multiplicity of problems dealing with the introduction of the stress, e.g., the introduction of greater individual stresses in sandwich shells with a GFP protective covering. We solved a task such as this in the manner shown, for example, in the schematic illustration (Figure 3).

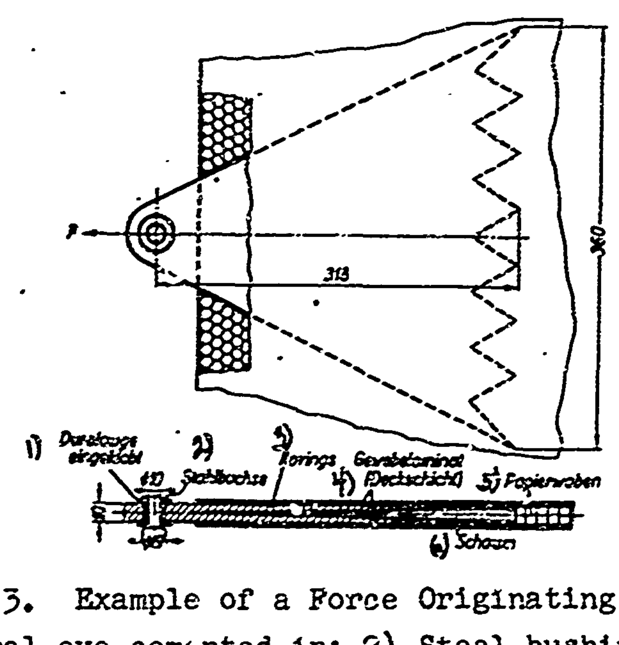

Fig. 3. Example of a Force Originating Point

KEY: 1) Dural eye cemented in; 2) Steel bushing; 3) Roving; 4) Fabric laminate (outer covering); 5) Paper honeycomb; 6) Foam.

The force originating point shown here is used to connect a frame structure of steel tubes to a truncated cone shaped GFP shell. On the tensile testing machine it withstood a 5 mp mean tensile strain. The weakest point was the eye itself.

The structure of the GFP material is closely related to the processing technology. What can be manufactured from fabrics or webbing, e.g., by hand methods, cannot, naturally be imitated with mattings or staple fibers, because the strength value and, consequently, the cross-sections vary greatly. Test values of the last mentioned type were not obtained by us, nor with laminates with other types of resins, e.g., phenols which, of course, also play a part in industry and which require elevated temperatures in order to age hardening. We also were unsuccessful in accumulating our own experiences with regard to one or the other technologies with GFP shells, as perhaps in the injection of rayon fibers according to the two-component injector process, which did not, however, promise the required light-construction quality for our purposes. For the experienced light-construction designer, it is of advantage, however, if he has had experience in other fields of technology and if he has the mechanical values from his experiences at his disposal.

Just as for the attainable strength the structure of our monocoque design is of great influence on the elasticity. Basically, the E-modulus of GFP and unfortunately, the subject E-modules (elasticity lengths) are also quite low. The comparison that was made in the beginning shows that the value of 1,000 km (see Figure 1) is less than 40% for the value for Dural and for St 60. Of course, the value was improved by suitable types of fabrics and perhaps also by changing to pre-stretched fibers; basically, however, there is always

a weakening of the GFP in this regard which from the beginning lead to, the determination that it is difficult to build rigid structures with GFP. Several examples would again bear this out (Figure 4).

Influence of the Type of Glass and Processing on Elasticity E/γ

Material	E-Modul $E \cdot 10^{-6}$ kp/cm^2	Spec. Grav. γ kp/dm^3	"E-Length" E/γ km
Mat Laminate	0,100	1.55	645
Fabric Laminate	0,180	1.8	1000
Roving profile	0,400	1.9	2100
Special "E" Glass (without resin)	0,750	2.6	2880
St 60.11 Steel (for comparison)	2,100	7.8	2690

Fig. 4.

We can see that the E-length is that much smaller the lower the weight of the laminate, i.e., the lower the glass content. Consequently, we could build a structure that is so rigid (and keeping the mass constant) the higher the quality of the material is so that the expense would also be increased. The demand for light-construction in connection with certain types of stresses, e.g., bending, buckling, torsion, brings about another constructive expenditure which leads to cross-sections with a high moment of inertia and a small cross-section. In connection with the problems touched on here it should also be stated that the designer must decide what he can expect from the GFP combination that he selected as to the most suitable shape of the cross-section. If, in his considerations a very low wall thickness results, then the fact that the stability requirements that result might have also increased should also be considered.

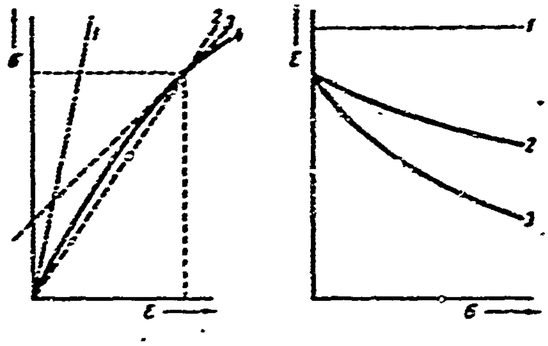

Fig. 5. Characteristic Stress-Strain Diagram for GFP (left) and the E-Patt rn (right). The curves represent the following: glass content as well as certain types of fabrics and fiber directions

1. Pure glass fibers
2. Secant modulus
3. Tangential modul s
4. Fabric Laminate

the four curves

If we find that the E-modulus is established for a specific GFP layout, then we must not forget that basically GFP is not a homogenous material. Even when laminates are stressed in the direction of the chain or the weft threads; thus, the E-modulus slowly decreases with increasing stress which can probably be the reason why the stressed fibers try to go in the direction of elongation. In diagonally stressed laminates this holds true to a greater extent and, furthermore, the same can be said for the G-modulus. It is, therefore, appropriate to check all the available, much too clear data on the elastic behavior which was intended for the E or G-modulus. We cannot be mislead by the fact that the glass fiber adheres very close to the Hook law (Fig. 5).

The structure of the high-modulus fiber is based on this consideration (Fig. 6).

3. Proposals for the Stess Analysis of Laminates

When building with thin GFP laminates or in determining the

stressed cross-section of a test specimen made of thin laminates, practical difficulties occur.

The local cross-section of the laminate (especially with the manual application method) is not constant, but dependent on the local resin content which can be quite irregular. The factor determining the strength, however, is the glass content and the resin content plays a very minor role. An attempt was, therefore, made to start from the cross-section unit (mm^2 or cm^2) and to refer to the number n of the fabric coverings contained in the cross-section. Instead of the standard stress formula

$$\sigma = \frac{P}{f} = \frac{P}{b \cdot s}\left[\frac{Kp}{cm^2}\right]$$

it would be more advantageous to use

$$\sigma^* = \frac{P}{b \cdot n}\left[\frac{Kp}{cm}\right],$$

i.e., the loading capacity of 1 cm of fabric width.

Quite similar manipulations can be considered for the tensile stress tau, the E-modulus and the G-modulus; on the other hand, this must not be met with difficulties, e.g., complete bending cross-section, when stress analyses are conducted with cross-section stresses that are uneven. Nevertheless, poorly utilized cross sections such as this are not taken into consideration for light construction. The resolved bending cross-section for the light constructions, on the other hand, tolerate the new process more or less the ratio girth height to the support height.

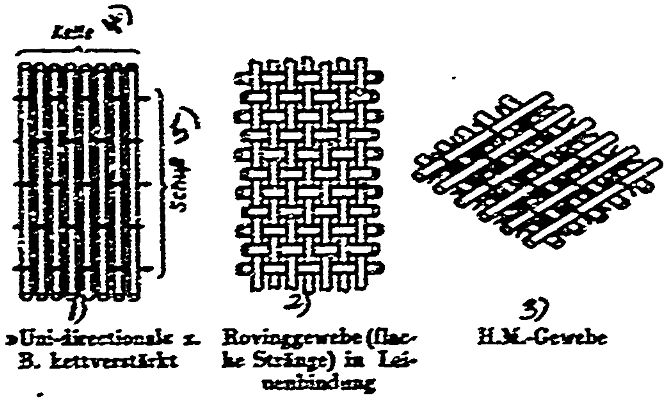

Fig. 6. Special Glass Fibers for Manufacturing High-Quality Laminate.
1) "Uni-directional" e.g., chain reinforced; 2) Roving fabric (flat strands) in linen binding; 3) H.M. Fabrics; 4) Chain; 5) Woof.

This proposal, undoubtedly, has the advantage that we have concrete stress data available which makes us independent of the varying glass content. It is assumed, of course, that the total strength of the laminate is composed of n number of similar strata. When this is not the case and the strata are composed of different types of fabrics or when the fibers that are bound to the shell are in different directions it then appears practical - and that is the way it was handled throughout this work - to subject the already determined stratum combinations pf the heterogenously constructed sheets to a subsequent control calculation in which, for example, we write:

$$\sigma' = \frac{P}{b \cdot \underset{\text{Shell}}{\text{Schale}}} \left[\frac{\text{Kp}}{\text{cm}}\right],$$

in which σ' represents the load per cm on the shell width. We must admit that this type of expression has very little general validity and that with calculations of this type we cannot without further ado calculate the required thickness of the shell. The experienced designer

knows other cases, however, in which he determined the thickness by experience and then made a control calculation. This method is also suitable in laboratory tests for determining the load bearing ability of an arbitrarily constructed shell having a width b. Consequently, in comparison to the first mentioned variant $\sigma^* = \frac{P}{b \cdot n}$, we still have the advantage that we are not restricted to a type of fabric that is the same and remains in the same direction. In the dimensionless factor "shell" the structure of the shell laminate remains, however. It contains the number, quality and fiber direction of the individual strata in connection with which, however, no restricting instructions regarding the glass content or the exact thickness of the shell are given as long as it is not necessary for other reasons.

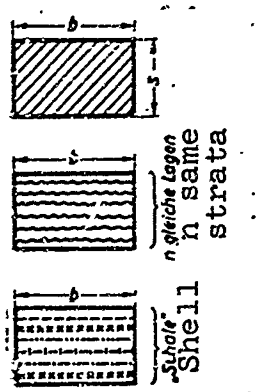

Fig. 7. To Define the "Covered" Stresses σ^* and σ' Cross-Section from:

1. homogenous material $\sigma = \frac{P}{b \cdot s}\left[\frac{kp}{cm^2}\right]$ of uniform stress distribution
2. laminated material $\sigma^* = \frac{P}{b \cdot n}\left[\frac{kp}{cm}\right]$ of equal strata n σ^* is the load bearing ability of a 1 cm wide fabric
3. laminated material of various $\sigma' = \frac{P}{Shell \cdot b}\left[\frac{kp}{cm}\right]$ strata of arbitrary arrangement σ' is the load bearing capacity of a 1 cm width of shell.

In determining the stress applied to transverse or torsion beams in which the loads are continuous or punctiform in nature, it is well known that a continuous or fluctuating variable strength is required of the load supporting cross-section. This requirement is satisfied quite well by GFP-fabric laminates, because it is simple to remove the number of fabric layers along the length of the beam as is required. GFP also fulfil requirements in respect to light construction materials, because designing the various cross-section strata doesn't present any difficulty whatsoever. As long as we want to conduct the control for the stress analysis according to the last mentioned method, it must, of course, be remembered that the load bearing capacity, according to the last mentioned method, must be known for every single type of "shell" which may occur over the entire length. In practice, of course, there are additional problems when dealing with pressure zones in transverse beams or torsionally stressed thin-walled hollow cross-sections. The already mentioned stability problem dealing with creases, bends, and the formation of bumps and folds which are to be presented by taking suitable measures which, however, as already mentioned, will not be discussed within the scope of this article.

4. Summary

GFP is a suitable material for the construction of highly stressed shells when it is properly layed out to correspond to the extent and type of stress to which it will be subjected. In so doing the designer benefits from the almost solitary fact that he can construct the material himself which means that he is able to select the parameters such as glass content, fiber strength and direction, type of webbing, type of resin, activators, hardening pressure and temperature, etc. so that an optimal ratio exists between the mechanical

characteristics that are desired (and possibly also the thermal, electrical, chemical, among others) and the required increase in material, saleries and general costs.

GFP is about 1.6 times lighter in weight than Al-alloys and about 4.5 times lighter than steel so that a laminate of the same weight results in a thicker wall which results in a local rigidity. Because of the high strength of GFP structures can, however, be lighter, in as much as the unfortunately only low E or G modulus of GFP permits a reduction in wall strength. Other methods of reducing the wall strength by means of stability criteria (folds, bends, etc.) were pointed out without, however, being treated in this connection.

Another point that makes the use of GFP commendable is the very high quality and its adaptability to the use of glues that proves to be more suitable in light construction than the use of screws and rivets the use of which, of course, is also possible.

This introductory report should give one an idea of the various standard constructions in which standard materials are used. I should, therefore, like to point out that there are no insurmountable difficulties if GFP is to be used in light construction but that it is more difficult if a rigid construction is desired. This requires a very high-quality material, specially designed monocoque constructions and in many cases, local reinforcements of the shell and these measures, of course, increase the costs. On the other hand, complicated shell forms made of GFP have the great advantage that they can easily be manufactured with the use of cheap equipment.

Whether GFP is to be considered satisfactory for the manufacture of highly stressed shells must be preceded by a very careful considera-tion of all the points and from case to case.

Concrete data on stress, technology, etc. was intentionally omitted in this report because these problems will be dealt with in detail in the subsequent report. My intention in this report was to clarify the fact that we are dealing here with serious problems which require the know-how and the knowledge of first class engineers.

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